

Original citation:

Linhart, Wojciech M., Gladysiewicz, Marta, Kopaczek, Jan, Rajpalke, Mohana, Ashwin, Mark J., Veal, Timothy David and Kudrawiec, Robert. (2017) Indium-incorporation enhancement of photoluminescence properties of Ga(In)SbBi alloys. Journal of Physics D: Applied Physics .

Permanent WRAP URL:

<http://wrap.warwick.ac.uk/90102>

Copyright and reuse:

The Warwick Research Archive Portal (WRAP) makes this work of researchers of the University of Warwick available open access under the following conditions.

This article is made available under the Attribution-NonCommercial-NoDerivatives 3.0 (CC BY-NC-ND 3.0) license and may be reused according to the conditions of the license. For more details see: <http://creativecommons.org/licenses/by-nc-nd/3.0/>

A note on versions:

The version presented in WRAP is the published version, or, version of record, and may be cited as it appears here.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk

Indium-incorporation enhancement of photoluminescence properties of Ga(In)SbBi alloys

This content has been downloaded from IOPscience. Please scroll down to see the full text.

Download details:

IP Address: 217.112.157.113

This content was downloaded on 13/07/2017 at 09:13

Manuscript version: Accepted Manuscript

Linhart et al

To cite this article before publication: Linhart et al, 2017, J. Phys. D: Appl. Phys., at press:

<https://doi.org/10.1088/1361-6463/aa7e64>

This Accepted Manuscript is: © 2017 IOP Publishing Ltd

During the embargo period (the 12 month period from the publication of the Version of Record of this article), the Accepted Manuscript is fully protected by copyright and cannot be reused or reposted elsewhere.

As the Version of Record of this article is going to be / has been published on a subscription basis, this Accepted Manuscript is available for reuse under a CC BY-NC-ND 3.0 licence after the 12 month embargo period.

After the embargo period, everyone is permitted to copy and redistribute this article for non-commercial purposes only, provided that they adhere to all the terms of the licence

<https://creativecommons.org/licences/by-nc-nd/3.0>

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permission will likely be required. All third party content is fully copyright protected, unless specifically stated otherwise in the figure caption in the Version of Record.

When available, you can view the Version of Record for this article at:

<http://iopscience.iop.org/article/10.1088/1361-6463/aa7e64>

Indium-incorporation enhancement of photoluminescence properties of Ga(In)SbBi alloys

W. M. Linhart,^{1,a)} M. Gladysiewicz,¹ J. Kopaczek,¹ M. K. Rajpalke,² M. J.

Ashwin,³ T. D. Veal,^{2,b)} and R. Kudrawiec^{1,c)}

¹*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*

²*Stephenson Institute for Renewable Energy and Department of Physics, School of Physical Sciences, University of Liverpool, Liverpool L69 7ZF, United Kingdom*

³*Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom*

Ga(In)SbBi alloys grown by molecular-beam epitaxy on GaSb substrates with up to 5.5% In and 1.8% Bi were studied by temperature- and power-dependent photoluminescence (PL) and compared to previous photoreflectance (PR) results. High energy (HE) and low energy (LE) PL peaks were observed and attributed respectively to Ga(In)SbBi bandgap-related emission and native acceptor-related emission. For GaSbBi below 100 K, the HE peak is at slightly lower energy than the bandgap determined from PR, indicating carrier localization. This phenomenon is significantly weaker in PL of GaInSbBi alloys, suggesting that the presence of indium improves the optical quality over that of GaSbBi.

Keywords: GaSbBi, GaInSbBi, mid infrared, photoluminescence, dilute bismides

^{a)} E-mail address: wojciech.linhart@pwr.edu.pl

^{b)} E-mail address: t.veal@liverpool.ac.uk

^{c)} E-mail address: robert.kudrawiec@pwr.edu.pl

I Introduction

Dilute III-V bismides are a very important class of highly mismatched alloys (HMAs) which have attracted great interest in recent years due to their unusual fundamental properties (including strong bandgap bowing, carrier localization at low temperatures, etc.), and their potential in the development of various optoelectronic devices operating in the mid-infrared spectral region [1-4]. It has been shown that a small quantity of Bi added to host GaSb material reduces the bandgap with a rate of $\sim 30\text{-}36$ meV/%Bi or 210 meV per $0.01/\text{\AA}$ change in lattice parameter [5-8]. Such bandgap reduction is caused by the downward shift of the conduction band due to Bi 6s states and the valence band anticrossing effect (VBAC)[9], in which Bi 6p states interact with GaSb valence bands, shifting the valence band maximum (VBM) upward [8].

Among dilute bismides grown on GaSb substrate, GaSbBi alloys were investigated relatively intensively in recent years [5-8,10-15]. However, only sporadic reports of GaInSbBi can be found in the literature [16-18]. Because the valence band offset between InSb and GaSb is negligible[19], In and Bi elements both reduce the bandgap of GaSb; In incorporation causes a downward shift of the conduction band minimum (CBM) and enhances the electron confinement when the material is used as a quantum well, while Bi lowers the CBM and simultaneously shifts the VBM up in energy[5,8], enhancing both electron and hole confinement in the case of quantum well. Apart from reducing the bandgap energy, diluted amounts of In and Bi in GaSb increase the lattice parameter because InSb and GaBi have lattice constant greater than that of GaSb [5,19]. In this context GaInSbBi quaternary alloys offer flexibility in the bandgap and band offset tuning in the mid-infrared in addition to what is already available from conventional III-V semiconductor alloys and dilute nitride antimonides [20,21]. Especially, GaSb-based dilute bismide alloys may offer means of overcoming the limitations of GaInAsSb alloys for achieving high continuous wave output power laser diodes at wavelengths beyond $2.7\text{ }\mu\text{m}$ at room temperature by improving the

quantum confinement potential for both electrons and holes, and hence improving a material gain in laser quantum wells [15,22,23].

In this paper, the temperature dependence and power dependence of emission studies of GaInSbBi quaternary alloys grown by molecular beam epitaxy (MBE) are presented. The optical properties of the alloys are studied using photoluminescence spectroscopy. Investigations are performed for GaInSbBi alloys with similar Bi content and In concentration ranging from 0 to 5.5%. It is clearly shown that incorporation of In into GaSbBi improves optical properties.

II Experimental Details

The GaInSbBi epilayers used for these studies were grown by solid-source MBE on un-doped (001) GaSb substrates at a nominal growth rate of $1.0 \mu\text{m h}^{-1}$. The sources and substrate preparation procedures are described elsewhere [5]. For each substrate, the oxide was removed under an incident Sb flux at approximately 550°C and then a 100 nm GaSb buffer layer was grown at 500°C . Thereafter, the substrate was cooled to 275°C and the GaInSbBi epilayer was grown. A determination of Ga:In ratio was done by growing a calibration layer of GaInSb with a thickness of ~ 100 nm. This layer was grown before the growth of GaInSbBi. Each GaInSbBi layer was grown using the same Ga and In fluxes as for the GaInSb layer, and the thickness of each GaInSbBi layer was ~ 300 nm. More details about the growth and composition determination using x-ray diffraction of the GaInSbBi samples can be found in Ref. 18.

The temperature dependent and laser power dependent photoluminescence (PL) was performed using a single grating 0.3 m focal length monochromator, along with a thermo-electrically cooled, InGaAs *pin* photodiode. A semiconductor laser (532 nm line and 80 mW) was used as an excitation source. The laser beam was focused onto the sample to a diameter of ~ 0.1 mm, and the power of the laser beam was tuned using a neutral density filter. Samples were mounted on a

cold finger in a helium closed-cycle refrigerator coupled with a programmable temperature controller, allowing measurements in the 15 to 290 K temperature range

III Results and discussion

Figure 1 shows temperature dependent PL spectra of $\text{GaSb}_{0.984}\text{Bi}_{0.016}$, $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, and $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ samples, taken in the temperature range from 15K to 290K and plotted with temperature increments of 20 K, but the first interval is 15K, from 15 K to 30 K. The excitation power used to obtain PL data was 80 mW. Additionally, the PL spectra are normalized to the peak maximum, to show the temperature dependence of the peak position. The PL peak, observed at 0.79 eV at temperatures below 100 K in GaInSbBi, is associated with a bound-exciton recombination in the GaSb buffer and/or substrate [24,25]. Below this peak, strong emission from GaSbBi (Fig. 1 (a)) or GaInSbBi (Figs. 1 (b) and (c)) is observed.

The epilayer-related emission consists of two PL peaks: a low-energy (LE) and a high-energy (HE) peak. The LE peak is observed at low temperatures below 90 K in the case of GaInSbBi and below 150 K in the case of GaSbBi alloys. The spectral position of the LE peak indicates that it is a defect-related emission in the epilayer and such localized emission is usually observed in narrow gap HMAs [7,26]. The second PL peak observed in the studied samples is the HE peak. At 15K temperature this peak is attributed to an exciton localization, however at temperatures above 100 K the HE peak is attributed to a band-to-band recombination in the epilayers, i.e. a recombination between delocalized states. The character of the HE peak is deduced from the comparison of the PL peak position with the bandgap determined from photoreflectance (PR) measurements in our previous studies on GaInSbBi layers (Ref. 18). Additionally, the HE peak has an asymmetric shape, which is typical for narrow gap semiconductors with significantly different effective masses for electrons and heavy holes. This can be attributed to a contribution of band-to band emission. Similar behaviour of the PL peak shape was observed in InNAsSb

layers [27]. Because of the narrow energy gap of GaInSbBi alloys, the free carrier emission starts to be important above 100 K and cannot be neglected.

Figure 2 shows the analysis of the spectral position of PL peaks for the $\text{GaSb}_{0.984}\text{Bi}_{0.016}$, $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, and $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ samples with the bandgap determined through PR measurements [18]. The overlap of the closed squares and open circles above 100K confirms that the HE peak is associated with the bandgap-related emission. At 15K the HE peak is attributed to an exciton localization. For the sample with In=0% the difference in energy between the band gap value and spectral position of the HE peak is ~ 0.014 eV (see Fig 2 (a)). After incorporation of In atoms it is clearly visible that the localization is weaker or even negligible (see Fig 2 (b) and (c)). All the studied samples have a similar Bi content. Therefore, it can be determined that the energy difference between LE and HE peaks decreases in the presence of In.

In order to determine the character of the PL emission, we performed PL measurements at various excitation powers and temperatures. Figure 3 shows example PL spectra collected from the $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ layer in the excitation power range of 2.5–80mW at three different temperatures. At 15 K the position of the LE peak shifts toward lower energies with decreasing excitation power, indicating the localized nature of this peak (Fig. 3(a)). At temperatures higher than 100 K the LE peak disappeared; only the HE peak was visible and a lack of spectral shift of this peak with changing the excitation power confirms the bandgap-related nature of this emission (Fig. 3(b) and (c)). A similar behavior of PL spectra with increasing excitation power was observed in the $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$ sample and also in ternary GaSbBi alloys [7].

It is well established that the PL intensity I_{PL} increases with the excitation power I_{ex} , and the relation can be expressed as

$$I_{PL} \propto I_{ex}^{\alpha}, \quad (1)$$

where the exponent α represents the type of recombination mechanism. For excitation laser light with energy exceeding the bandgap energy, the exponent α is generally between 1 and 2. $\alpha = 1$ for the purely excitonic emission (free- and bound-exciton emission), and α is less than 1 for free-to-bound and donor-acceptor pair recombination. α equals 2 indicates a band to band recombination [28]. Analysis of the $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$ (Fig. 4(a)) yields a PL intensity versus pump power α coefficient of 1.5 at 290 K and α of 0.7 at 15 K. Similarly, analysis of the $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ (Fig. 4 (b)) yields α of 1.6 at 290 K and α of 0.85 at 15 K. At low temperature the α is less than 1, suggesting a free-to-bound and/or donor-acceptor pair recombination. The excitons tend to be localized and cannot reach nonradiative recombination centers. In this case free excitons can be efficiently trapped by local potentials related to fluctuations of Bi and In [29,30]. As temperature is increased up to room temperature, the character of the PL changes substantially (the α coefficient is bigger than 1.5). At this temperature limit, the excitons are free due to a thermal activation and coexist with free carriers. These can now reach nonradiative recombination centers. Consequently a nonradiative recombination dominates and reduces the number of excitons which could recombine radiatively. As a result, the PL intensity becomes weaker at the same level of excitation. However, an observation of quite strong PL up to room temperature means that the concentration of native defects (non-radiative centers) is relatively low for these alloys.

To explain the nature of LE emission the electronic band structure has been calculated within the 14-band *kp* model [23] with the Bi-related shift of conduction and valence band anticrossing (VBAC) parameters tuned to obtain agreement with experimental data [31]. The VBAC model coupling parameter was found to be ~ 1.5 eV. The compressive strain in Ga(In)AsBi layers has been taken into account according to the Bir-Pikus theory as shown in detail in Ref. [22] Figure 5 shows the dispersion of the conduction and valence bands for the three Ga(In)SbBi samples near

the center of the Brillouin zone (thick solid lines) together with the conduction and valence band dispersions in Ga(In)Sb as the reference (red dashed lines). First it is clearly visible that the incorporation of Bi atoms into Ga(In)Sb host leads to type I bandgap alignment between GaSb and Ga(In)SbBi, which is very important for applications of this alloy in GaSb-based quantum wells dedicated for light emitters. Second it is observed that the bandgap calculated for the three alloys is very consistent with the spectral position of the HE peak in PL spectra while the spectral position of the LE peak can be explained by the radiative recombination between the conduction band and an acceptor level, which is observed at very similar energy. In general such a situation is expected for deep levels and therefore the LE emission is attributed to free-to-bound (deep acceptor) recombination, which is consistent with the power dependent PL measurements and the analysis of the α parameter for the LE peak. This conclusion is also consistent with our previous studies for GaSbBi alloys of various Bi concentrations [7].

Comparing PL spectra for In-free and In-containing samples, we conclude that indium improves optical properties in this material system: the contribution of the LE peak to the PL spectrum is smaller, the thermal quenching of the HE peak is weaker, and the broadening of the HE peak is smaller for In-containing samples. Therefore we are fully convinced that this alloy is very promising for applications in light emitters.

IV Conclusions

In summary, LE and HE emissions from GaInSbBi layers have been identified in PL spectra. The comparison of the HE peak position with the results obtained from photoreflectance measurements, and the asymmetric shape of the HE peak indicates it is due to bandgap-related emission. At low temperatures, the LE peak is observed and it is attributed to defect-related emission. The energy separation between HE and LE peak decreases with increasing In concentration. Additionally, at low temperatures the HE peak for GaSbBi is up to 0.014 eV below

the bandgap determined by PR as a result of carrier localization. The localization energy is significantly reduced for the GaInSbBi alloys, suggesting the presence of indium improves the optical quality over that of GaSbBi alloys.

Acknowledgements

This work was performed within the grant of the National Science Centre, Poland (Grant No. 2014/13/D/ST3/01947). In addition, MG acknowledges financial support from the NCN Poland (Grant No. 2013/10/E/ST3/00520). JK acknowledges financial support from the NCN Poland (Grant No. 2015/17/N/ST3/02286). TDV acknowledges financial support from the Engineering and Physical Sciences Research Council (EPSRC) (Grant No. EP/G004447/2).

References

- [1] Tixier S, Adamczyk M, Tiedje T, Francoeur S, Mascarenhas A, Wei P and Schiettekatte F 2003 Molecular beam epitaxy growth of $\text{GaAs}_{1-x}\text{Bi}_x$ *Appl. Phys. Lett.* **82**, 2245
- [2] Tiedje T, Young E C and Mascarenhas A 2008 Growth and properties of the dilute bismide semiconductor $\text{GaAs}_{1-x}\text{Bi}_x$ a complementary alloy to the dilute nitrides *Int. J. Nanotechnol.* **5**, 963
- [3] Lu X, Beaton D A, Lewis R B, Tiedje T and Zhang Y 2009 Composition dependence of photoluminescence of $\text{GaAs}_{1-x}\text{Bi}_x$ alloys *Appl. Phys. Lett.* **95**, 041903
- [4] Pursley B, Luengo-Kovac M, Vardar G, Goldman R S and Sih V 2013 Spin lifetime measurements in GaAsBi thin films *Appl. Phys. Lett.* **102** 022420
- [5] Rajpalke M K, Linhart W M, Birkett M, Yu K M, Scanlon D O, Buckeridge J, Jones T S, Ashwin M J and Veal T D 2013 Growth and properties of GaSbBi alloys *Appl. Phys. Lett.* **103** 142106
- [6] Rajpalke M K, Linhart W M, Yu K M, Alaria J, Kopaczek J, Kudrawiec R, Jones T S, Ashwin M J and Veal T D 2014 High Bi content GaSbBi alloys *J. Appl. Phys.* **116** 043511

- [7] Kopaczek J, Kudrawiec R, Linhart W, Rajpalke M, Jones T, Ashwin M and Veal T 2014 Low- and high-energy photoluminescence from $\text{GaSb}_{1-x}\text{Bi}_x$ with $0 < x \leq 0.042$ *Appl. Phys. Express* **7** 111202
- [8] Polak M P, Scharoch P, Kudrawiec R, Kopaczek J, Winiarski M J, Linhart W M, Rajpalke M K, Jones T S, Ashwin M J and Veal T D 2014 Theoretical and experimental studies of electronic band structure for $\text{GaSb}_{1-x}\text{Bi}_x$ in the dilute Bi regime *J. Phys. D: Appl. Phys.* **47** 355107
- [9] Alberi K, Wu J, Walukiewicz W, Yu K M, Dubon O D, Watkins S P, Wang C X, Liu X, Cho Y J and Furdyna J 2007 Valence-band anticrossing in mismatched III-V semiconductor alloys *Phys. Rev. B* **75** 045203
- [10] Das S K, Das T D, Dhar S, De La Mare M and Krier A 2012 Near infrared photoluminescence observed in dilute GaSbBi alloys grown by liquid phase epitaxy *Infrared Phys. Technol.* **55** 156
- [11] Das S K, Das T D and Dhar S 2014 Effect of post-growth anneal on the photoluminescence properties of GaSbBi *Semicond. Sci. Technol.* **29** 015003
- [12] Duzik A and Millunchick J M 2014 Surface morphology and Bi incorporation in GaSbBi(As)/GaSb films *J. Cryst. Growth* **390** 5
- [13] Song Y, Shumin W, Roy I S, Shi P and Hallen A 2012 Growth of $\text{GaSb}_{1-x}\text{Bi}_x$ by molecular beam epitaxy *J. Vac. Sci. Technol. B* **30** 02B114
- [14] Delorme O, Cerutti L, Tournié E, Rodriguez J -B 2017 Molecular beam epitaxy and characterization of high Bi content GaSbBi alloys *J. Cryst. Growth* - in press
- [15] Delorme O, Cerutti L, Luna E, Narcy G, Trampert A, Tournié E, Rodriguez J -B 2017 GaSbBi/GaSb quantum well laser diodes *Appl. Phys. Lett.* **110** 222106
- [16] Hayakawa Y, Ando M, Matsuyama T, Hamakawa E, Koyama T, Adachi S, Takahashi K, Lifshits V G and Kumagawa M 1994 Diffusion of both Ga and Bi into InSb seeds during growth of InGaSbBi *J. Appl. Phys.* **76** 858
- [17] Du Q, Alperin J and Wang W 1997 Molecular beam epitaxial growth of GaInSbBi for infrared detector applications *J. Cryst. Growth* **175/176** 849

- [18] Kopaczek J, Rajpalke M K, Linhart W M, Jones T S, Ashwin M J, Kudrawiec R and Veal T D 2014 Photoreflectance spectroscopy of GaInSbBi and AlGaSbBi quaternary alloys *Appl. Phys. Lett.* **105** 112102
- [19] Vurgaftman I, Meyer J R and Ram-Mohan L R 2001 Band parameters for III-V compound semiconductors and their alloys *J. Appl. Phys.* **89** 5815
- [20] Wang D, Svensson S P, Shterengas L, Belenky G, Kim C S, Vurgaftman I and Meyer J R 2009 Band edge optical transitions in dilute-nitride GaNSb *J. Appl. Phys.* **105** 014904
- [21] Ashwin M J, Walker D, Thomas P A, Jones T S and Veal T D 2013 N incorporation in GaInNSb alloys and lattice matching to GaSb *J. Appl. Phys.* **113** 33502
- [22] Gladysiewicz M, Kudrawiec R and Wartak M S 2015 8-band and 14-band kp modeling of electronic band structure and material gain in Ga(In)AsBi quantum wells grown on GaAs and InP substrates *J. Appl. Phys.* **118** 055702
- [23] Gladysiewicz M, Kudrawiec R and Wartak M S 2016 Electronic band structure and material gain of III-V-Bi quantum wells grown on GaSb substrate and dedicated for mid infrared spectral range *J. Appl. Phys.* **119** 075701
- [24] Meinardi F, Parisini A and Tarricone L 1993 A study of the electrical properties controlled by residual acceptors in gallium antimonide *Semicond. Sci. Technol.* **8** 1985
- [25] Rouillard Y, Lambert B, Toudic Y, Baudet M and Gauneau M 1995 On the use of dimeric antimony in molecular beam epitaxy *J. Cryst. Growth* **156** 30
- [26] Kudrawiec R, Latkowska M, Baranowski M, Misiewicz J, Li L H and Harmand J C 2013 Photoreflectance, photoluminescence, and microphotoluminescence study of optical transitions between delocalized and localized states in $\text{GaN}_{0.02}\text{As}_{0.98}$, $\text{Ga}_{0.95}\text{In}_{0.05}\text{N}_{0.02}\text{As}_{0.98}$ and $\text{GaN}_{0.02}\text{As}_{0.90}\text{Sb}_{0.08}$ layers *Phys. Rev. B* **88** 125201
- [27] Latkowska M, Kudrawiec R, Janiak F, Motyka M, Misiewicz J, Zhuang Q, Krier A and Walukiewicz W 2013 Temperature dependence of photoluminescence from InNAsSb layers: the

role of localized and free carrier emission in determination of temperature dependence of energy gap *Appl. Phys. Lett.* **102** 122109

[28] Schmidt T, Lischka K and Zulehner W 1992 Excitation-power dependence of the near-band-edge photoluminescence of semiconductors *Phys. Rev. B* **45** 8989

[29] Norman A G, France R and Ptak A J 2011 Atomic ordering and phase separation in MBE *J. Vac. Sci. Technol. B.* **29** 03C121

[30] Imhof S, Thränhardt A, Chernikov A, Koch M, Köster N S, Kolata K, Chatterjee S, Koch S W, Lu X, Johnson S R, Beaton D A, Tiedje T and Rubel O 2010 Clustering effects in Ga(AsBi) *Appl. Phys. Lett.* **96** 131115

[31] Polak M P, Scharoch P and Kudrawiec R 2015 First-principles calculations of bismuth induced changes in the band structure of dilute Ga-V-Bi and In-V-Bi alloys: Chemical trends versus experimental data *Semicond. Sci. Technol.* **30** 094001

Fig1. Temperature dependence of PL spectra for (a) $\text{GaSb}_{0.984}\text{Bi}_{0.016}$, (b) $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, and (c) $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$. All the spectra are normalized to the peak maximum. The peaks observed at 0.79 eV and 0.81 eV at 15K, correspond to bound-exciton and free exciton recombinations, respectively in the GaSb substrate or buffer [24,25]. The spectra were collected at the excitation power of 80 mW.

Fig 2. (Color online) Energies of LE and HE PL peak maxima, obtained from peak fitting (open circles) and the bandgap determined from PR measurements (closed squares) (a) $\text{GaSb}_{0.984}\text{Bi}_{0.016}$ (results taken from Ref. 7), (b) $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, and (c) $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$. PR results of (a) are adopted from [7], (b) and (c) are reproduced from [18], with the permission of AIP Publishing.

Fig 3. (Color online) PL spectra for a $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ layer at various excitation powers at (a) 15 K, (b) 110 K and (c) 290 K. A vertical dashed blue line denotes the position of the LE peak at 80 mW excitation power. Solid blue lines indicate the shift of the peak maximum with changing the excitation power.

Fig. 4. (Color online) PL intensity of GaInSbBi samples measured at 15 K, 110 K and 290K with different excitation power. Lines show fits to the relation (1). (a) $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, (b) $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$.

Fig. 5. (Color online) Electronic band structure of (a) $\text{GaSb}_{0.984}\text{Bi}_{0.016}$, (b) $\text{Ga}_{0.967}\text{In}_{0.033}\text{Sb}_{0.982}\text{Bi}_{0.018}$, and (c) $\text{Ga}_{0.945}\text{In}_{0.055}\text{Sb}_{0.987}\text{Bi}_{0.013}$ near the center of the Brillouin zone (thick solid lines) together with the electronic band structure of Bi-free host as the reference (red dashed lines). The position of the deep acceptor level is established on the basis of the LE peak position in PL spectra.

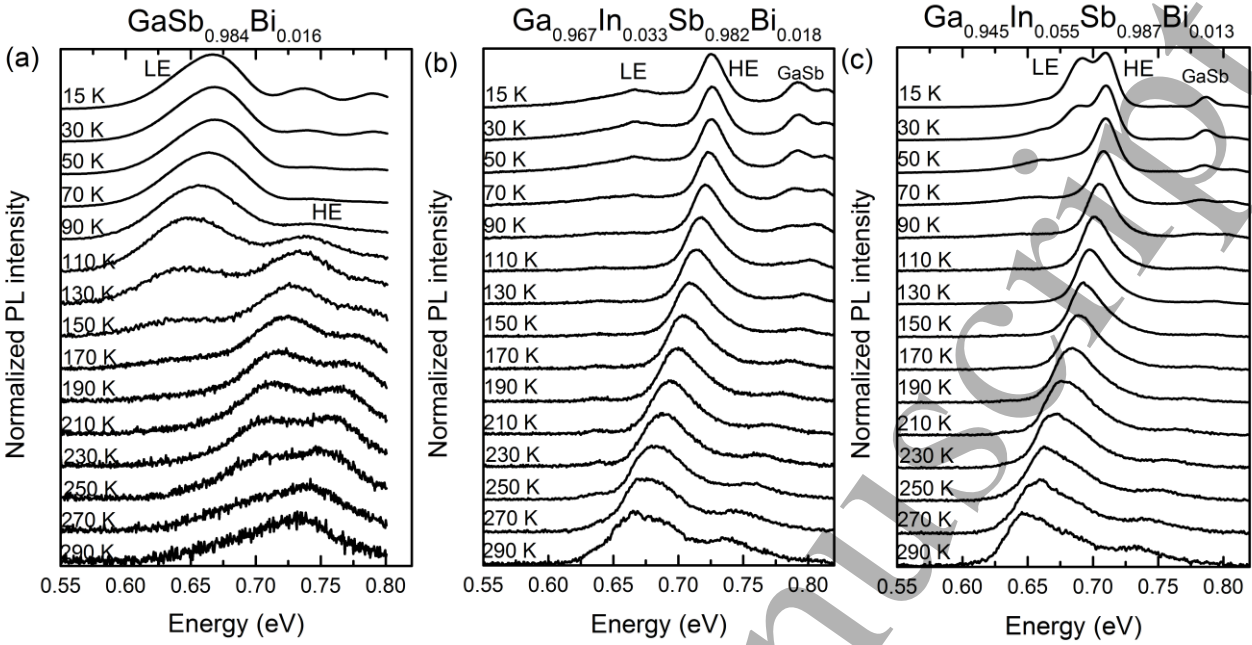


Fig. 1. (W. M. Linhart et al.)

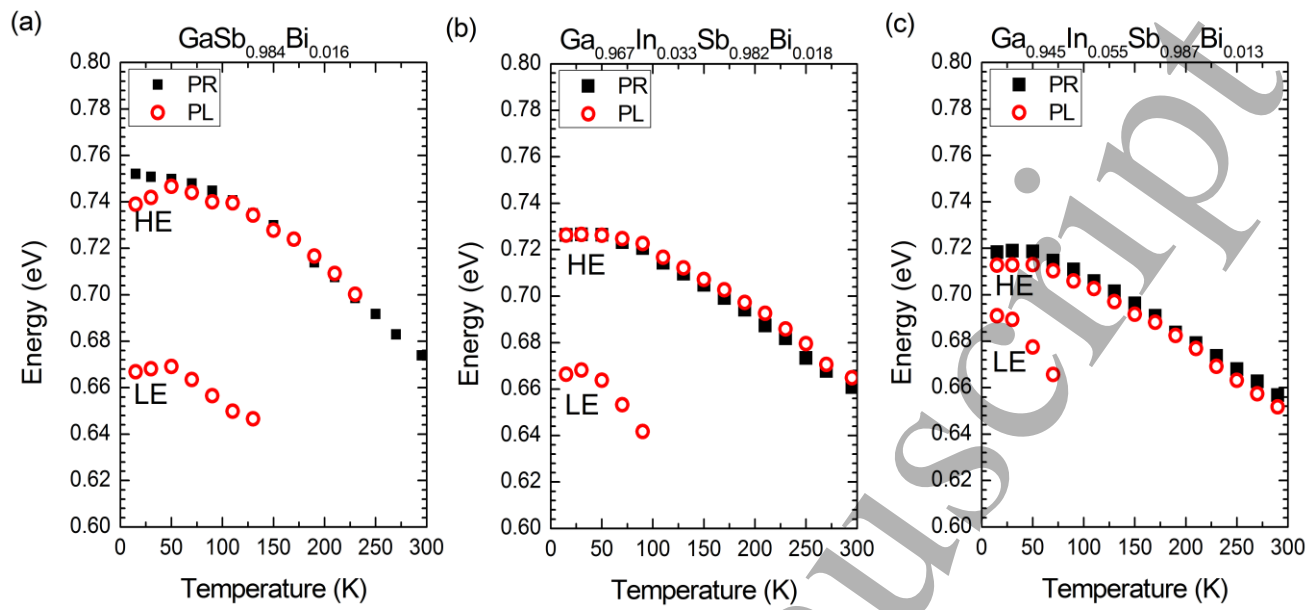


Fig. 2. (W. M. Linhart, et al.)

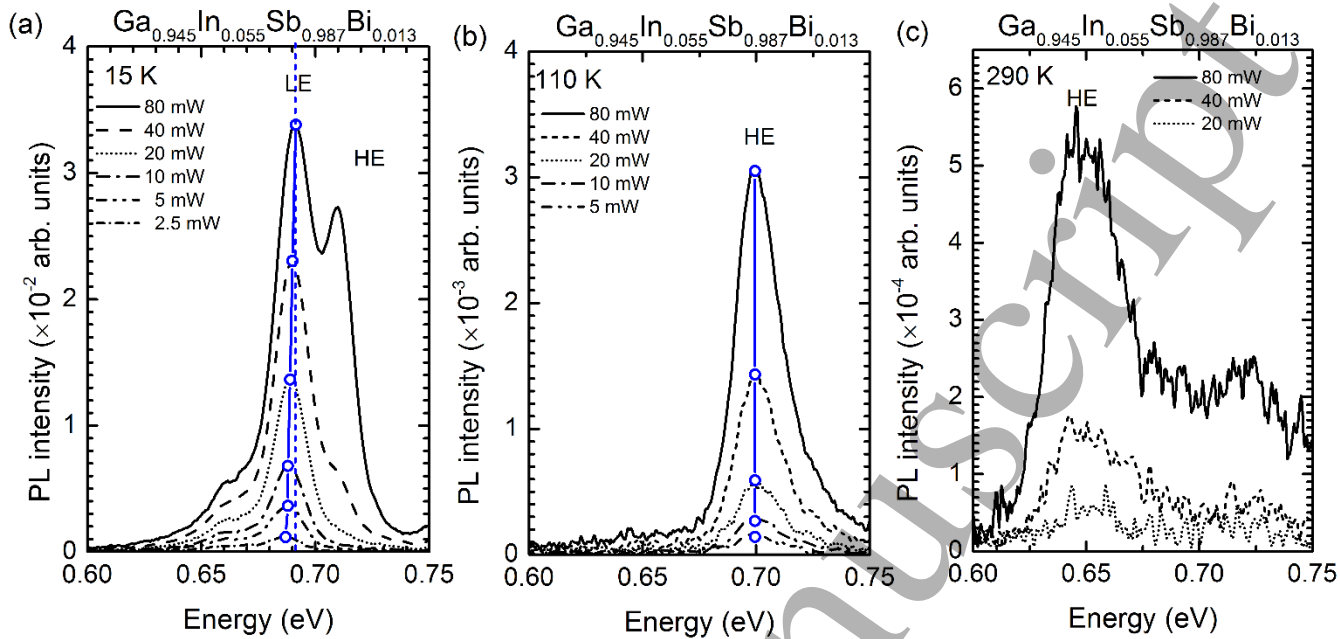


Fig. 3. (W. M. Linhart, et al.)

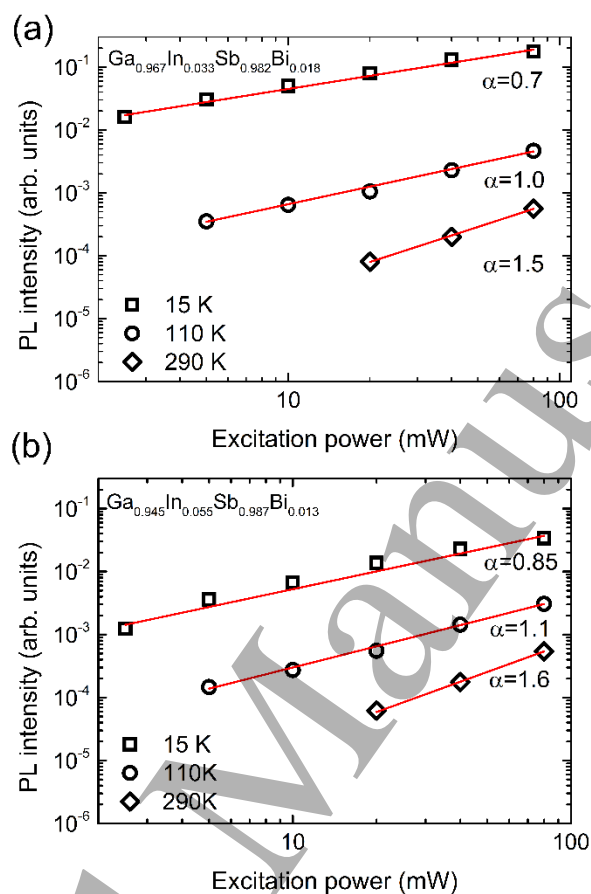


Fig. 4. (W. M. Linhart, et al.)

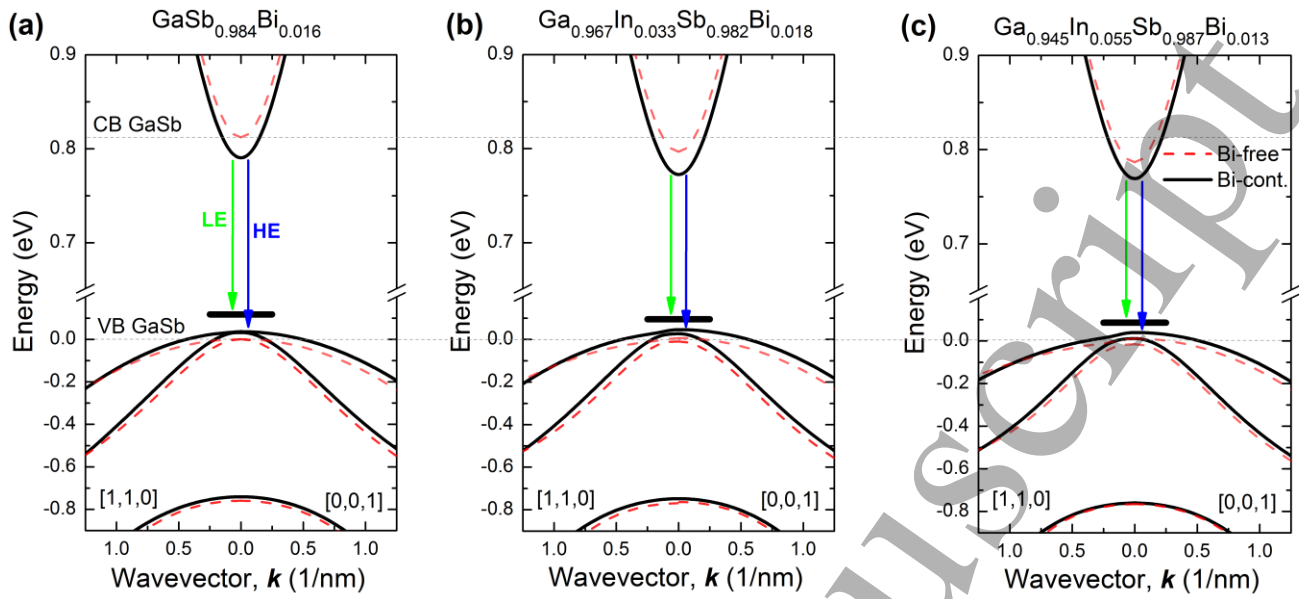


Fig. 5. (W. M. Linhart, et al.)